Magnetic source localization via linearly constrained minimum variance spatial filtering

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1 Introduction

Spatial filtering has a long history of successful application in radar and sonar problems (e.g. [1,2]). The process of spatial filtering is also known as beamforming, since early spatial filters were designed to form pencil beams for either receiving or transmitting signals. More recently, spatial filtering has been applied to EEG and MEG [3–6, 8] to localize intracranial sources of electrical activity and to eliminate noise and interference from the recorded time series.

Spatial filtering can be used to localize sources by building a large number of filters, each designed to pass signal from one location and reject signal from others. The power—or some other measure of signal strength—at the output of each filter is evaluated and depicted as a function of the filter's passband location. Locations with relatively large values of power are likely to represent strong sources of activity. This technique has been used by van Drongelen et al. [8] to successfully localize known sources associated with bilateral median nerve somatasenory evoked potentials, occipital spikes, and to reject eye movement artifacts from spike activity. Van Veen et al., [6] used spatial filtering to localize stimulating electrodes, i.e. current dipoles, implanted in the brain.

In this paper we demonstrate the use of linearly-constrained minimum variance (LCMV) spatial filtering in the following situations: 1) localization of neural sources in the presence of large artifact from magnetic objects on the subject, 2) localization of two closely spaced brain regions that are active simultaneously, and 3) localization of spontaneous brain activity.

2 Methods

2.1 Data model and LCMV neural activity index calculation

The medium is assumed to be linear so the signal recorded by the sensor at any given time is the superposition of signals from L active sources at locations $\mathbf{q_i}$ plus noise:

$$\mathbf{x} = \sum_{i=1}^{L} \mathbf{H}(\mathbf{q_i})\mathbf{m}(\mathbf{q_i}) + \mathbf{n} \tag{1}$$

where $\mathbf{H}(\mathbf{q_i})$ is forward solution matrix [7], $\mathbf{m}(\mathbf{q_i})$ is the dipole moment at the location $\mathbf{q_i}$.

Using the LCMV approach, Van Veen et al. defined a neural activity index (NAI), which estimates the source-to-noise variance power as a function of location [6]:

$$NAI(\mathbf{q_0}) = \frac{tr\left\{\left[\mathbf{H}^T(\mathbf{q_0})\mathbf{C}^{-1}(\mathbf{x})\mathbf{H}(\mathbf{q_0})\right]^{-1}\right\}}{tr\left\{\left[\mathbf{H}^T(\mathbf{q_0})\mathbf{Q}^{-1}\mathbf{H}(\mathbf{q_0})\right]^{-1}\right\}} \tag{2}$$

where $\mathbf{C}(\mathbf{x})$ is data and $\mathbf{Q}$ is noise covariance matrices respectively. Regions with high NAI have large variance and presumably have high neural activity.

As it can be seen from (2) neural activity index requires knowledge of the data covariance matrix $\mathbf{C}(\mathbf{x})$. In practice it is unknown and must be estimated from the data:

$$\widetilde{\mathbf{C}}(\mathbf{x}) = \frac{1}{M-1}\sum_{n=1}^{M}(\mathbf{x_n} - \bar{\mathbf{x}})(\mathbf{x_n} - \bar{\mathbf{x}})^T \tag{3}$$

where $\bar{\mathbf{x}}$ is the sample mean and $\mathbf{x_n}$ n = 1, 2, …, M are observations of the phenomena to be localized. The number of observations *M* must at least exceed the number of elements in each data vector. A common rule of thumb for reliable covariance matrix estimation is three-four times the number of data channels recorded [6].

2.2 Simultaneous activation of two brain regions

A 37-channel SQUID magnetometer (Magnes, Biomagnetic Technologies) was used to record the MEG data for all experiments.

In this study two stimuli were presented simultaneously—lip and index finger stimulation, auditory and lip stimulation, or auditory and index finger stimulation—in order to activate two closely-spaced brain regions. For each run, 150 0.4-sec epochs were digitized at a sampling rate of 297.6 Hz. Data were passband filtered from 1-50 Hz and notch filtered at 60 Hz. Separate recordings with index finger stimulation alone, lip stimulation alone, and auditory stimulation alone were taken for comparison. Equivalent current dipole (ECD) locations were compared with the location of peaks in the NAI.

2.3 Artifact-contaminated data processing

Artifact-contaminated data was acquired from a normal subject by attaching a small magnetic object to her face during a somatosensory evoked response measurement. The interference from the magnetic object was intended to simulate artifact from dental work, which is a common problem in patient studies. Somatosensory recordings without artifact were taken from the same subject for comparison. Data acquisition parameters and preprocessing steps were similar to the ones described above.

2.4 Alpha rhythm analysis

Four young adults subjects participated in this part of the study. The sensors were positioned over the occipital hemisphere, and MEG was recorded continuously for over 2 minutes. The subjects were instructed to keep their eyes open for the first half of the measurement, and to close them for the second half. Dipole fitting and the LCMV method were applied to the second half of the data. Data were first filtered to pass only frequencies in the range of alpha oscillations (8-12 Hz). EDCs and the NAI were overlaid onto MR images.

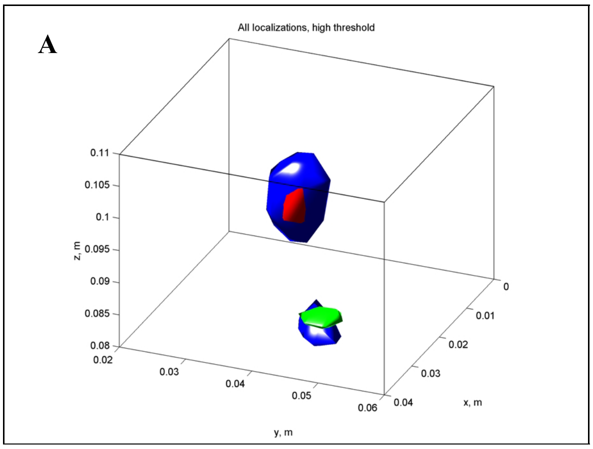

Figure 1A. *Overlay of localizations: red – index finger, green – lip, blue – simultaneous stimulation of index finger and lip.*

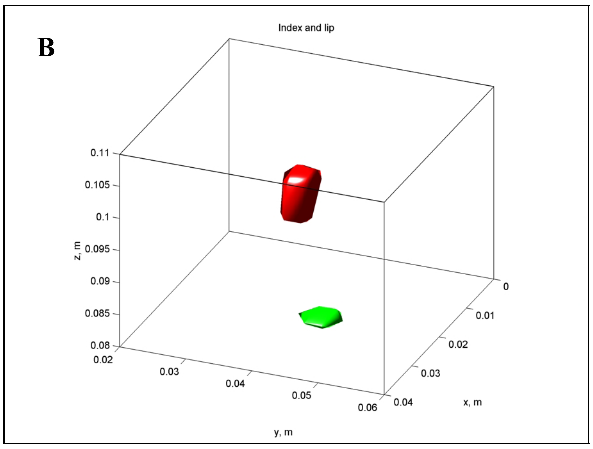

Figure 1B. *Index finger and lip stimulation as separate experiments.*

3 Results

3.1 Simultaneous activation of two brain regions

For simultaneous somatosensory stimulation of two parts of the body or simultaneous auditory/somatosensory, the EDCs were scattered diffusely around the two activated regions, while the LCMV method was capable of resolving the two activated regions as distinct (Fig. 1A,B). The ability of the spatial filter to resolve two closely-spaced sources depends on a number of factors, including the degree of correlation of the sources and the threshold for activation used to plot the NAI. In Fig. 1 a high threshold was used. As the threshold is lowered, the activated regions grow in size and eventually merge together.

3.2 Artifact-contaminated data processing

The LCMV method can accurately localize sources in the presence of strong artifact (Fig. 2).

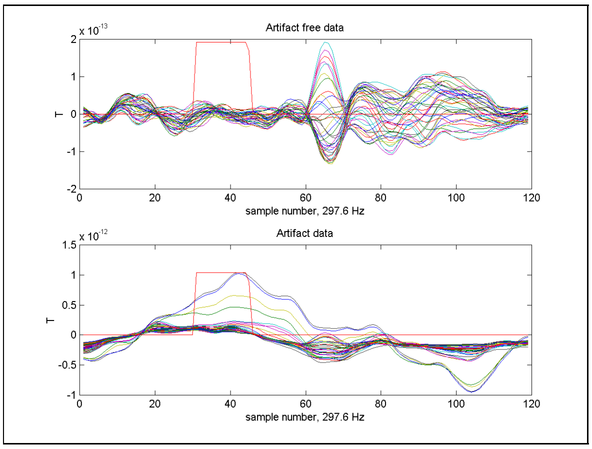

Figure 2. *Signal without (upper) and with (lower) artifact present in the data during somatosensory experiment.*

We show first in Fig. 3A that in the absence of artifact there is good agreement between the source locations deduced by dipole fits and the LCMV method. But for artifact-contaminated data dipole fitting fails, whereas the LCMV method still gives correct results (Fig. 3B).

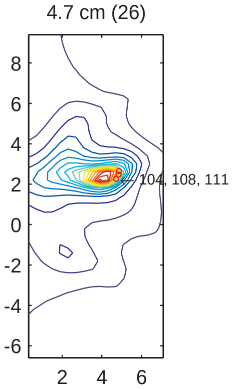

Figure 3A. *LCMV localization with artifact-free data. Good agreement with dipole fitting is obtained. Single slice shown. Numbers on the plot – dipole latencies in milliseconds.*

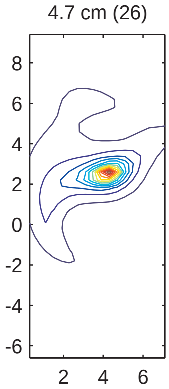

Figure 3B. *LCMV localization on artifact-contaminated data. The source location is the same as with artifact-free data (Fig. 3A); however, dipole fitting fails.*

3.3 Alpha rhythm analysis

For analysis of spontaneous brain activity, such as alpha rhythm, the large number of ECDs obtained from the data—approximately 1500 here—constitutes a main disadvantage of the use of dipole fitting. Visualization of so many dipoles on a set of MR images is difficult (Fig. 5). In contrast, the LCMV result is easier to visualize and interpret. Fig. 4 shows the localization of neural activity by means of the LCMV method. Peripheral occipital cortex is activated, as well as the macular region, along the lingula of the occipital lobe. In Fig. 5 a superposition of the results of dipole fitting and the LCMV method is presented. There is a good agreement between the ECD clusters and the LCMV localization.

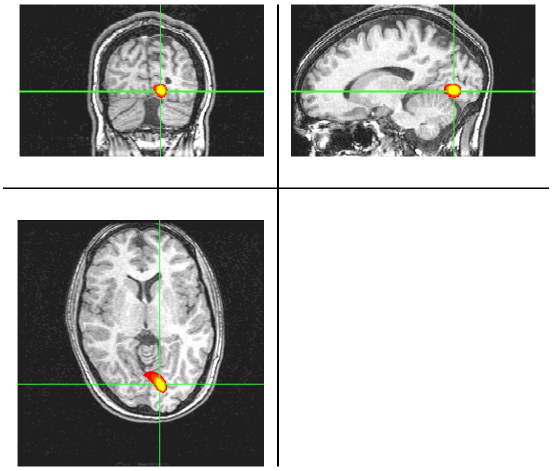

Figure 4. *Localization of alpha rhythm as deduced by LCMV algorithm*

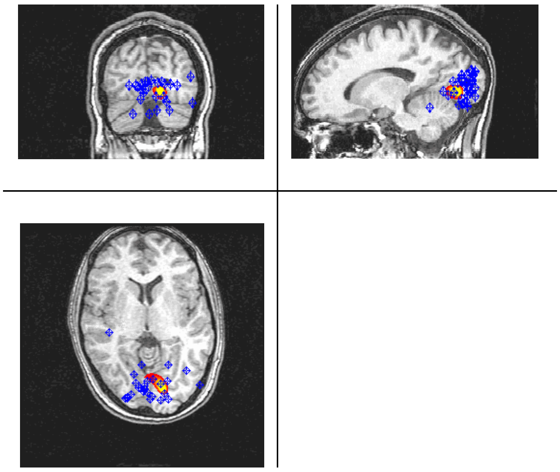

Figure 5*. ECDs are scattered and more difficult to interpret.*

4 Discussion

Our results show that spatial filtering using the LCMV algorithm is effective for localization of sources of evoked and spontaneous MEG. As with most covariance-based methods, it has the ability to resolve sources with separations on the order of a cm, and is excellent for minimizing the influence of artifact. In addition, the LCMV method requires no *a priori* assumptions about the number of sources or their geometry, and is therefore a very convenient method of localizing spontaneous brain activity.

References

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